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RESPONSE OF BUILDINGS TO NEAR-FIELD PULSE-LIKE GROUND MOTIONS

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SUMMARY

Ground motions affected by directivity focusing at near-field stations contain distinct pulses in acceleration, velocity, and displacement histories. For the same Peak Ground Acceleration (PGA) and duration of shaking, ground motions with directivity pulses can generate much higher base shears, inter-storey drifts, and roof displacements in high-rise buildings as compared to the 1940 El Centro ground motion which does not contain these pulses. Also, the ductility demand can be much higher and the effectiveness of supplemental damping lower for pulse-like ground motions. This paper presents a simple interpretation of the response characteristics of three recorded and one synthetic near-field ground motions. It is seen that for pulse-like ground motions—similar to any other ground motion—the Peak values of Ground Acceleration, Velocity, and Displacement (PGA, PGV and PGD) are the key response parameters. Near-field ground motions with directivity effects tend to have high PGV/PGA ratio, which dramatically influences their response characteristics. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: near-field; near-fault near-source; pulse-like; ground motions; earthquake; tall buildings; base isolation; building code

INTRODUCTION

Ground motions affected by directivity focusing at near-field stations contain distinct pulses in the acceleration, velocity, and displacement histories.[1–3] In a strike-slip earthquake, if the rupture propagates in the direction of the recording station, the coherently travelling long-period waves result in large values of ground velocities and displacements in the fault-normal direction.[4] Because the high-frequency waves are less likely to travel in a coherent manner, the ground accelerations are relatively unaffected by directivity focusing. The effect of directivity focusing is most pronounced on displacements, less on velocities, and least on accelerations.[5] Directivity focusing can also occur for dip-slip faulting, although the conditions required are met less readily than for strike-slip faulting.[4]

Bertero *et al.*,[6] and Anderson and Naeim[7] showed that near-field ground motions with pulses can induce dramatically high response in fixed-base buildings. Anderson and Bertero[8] pointed out that the wide acceleration pulses are especially damaging if the width of the pulse is large compared with the natural period of the structure. Hall *et al.*,[9] in their study of buildings

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subjected to artificially generated pulse-like ground motions, indicated that the demands imposed by the displacement pulses in the near-field ground motions can far exceed the capacity of flexible high-rise and base-isolated buildings designed to current standards. Iwan[10] stated that the pulses in the near-field ground motions travel through the height of the buildings as waves, and that the conventional techniques using the modal superposition method and the response spectrum analysis may not capture the effect of these pulses. Iwan[10] also proposed the use of drift spectrum for near-field ground motions. Chopra and Chintanapakdee,[11] in their preliminary investigation, concluded that the response spectrum analysis is accurate for engineering applications and should be preferred over the drift spectrum.

The objectives of this paper are to: (1) clarify—through simple analysis and interpretation—some of the issues related with the effects of pulse-like ground motions; (2) identify the key response parameters for pulse-like ground motions; and (3) comment on the suitability of the conventional methods of analysis of buildings subjected to pulse-like ground motions.

NEAR-FIELD GROUND MOTIONS

The following four near-field ground motions are studied in this paper:

(a) 1940 El Centro: The 1940 El Centro ground motion was recorded during a M6.9, strike-slip earthquake, at a soil site located roughly 8 km from the surface projection of the fault.[12] The acceleration, velocity, and displacement histories of the North–South El Centro ground motion are shown in Figure 1(a). There are several different versions of the El Centro record in existence (e.g. References 13 and 14). The version shown in Figure 1(a) is taken from Reference 14. The El Centro ground motion is one of the earliest recorded and most widely used near-field ground motions. It does not contain pulses in the acceleration, velocity, or displacement histories.

(b) 1979 Imperial Valley: Shown in Figure 1(b) are the plots of the 1979 Imperial Valley (array #5) ground motion recorded at a soil site, in S50W direction, during a M6.5 strike-slip earthquake.[15] The site was located roughly 1 km from the surface projection of the fault. The Imperial Valley ground motion does contain distinct pulses in the acceleration, velocity, and displacement histories.

(c) Synthetic ground motion: The plots shown in Figure 1(c) are of a synthetic ground motion, previously used by Hall *et al.*[9] in their analyses of flexible buildings subjected to near-field ground motions. This ground motion is for a soil site located 15 km from the surface projection of a blind-thrust fault generating a M7 earthquake. A prominent pulse in the acceleration history causes the ground acceleration to remain near its peak for almost 1 s. This, in turn, leads to large velocity and displacement pulses.

(d) 1994 Sylmar: Shown in Figure 1(d) are the plots of the ground motion recorded at a soil site, in the North–South direction, during M6.7 1994 Northridge Earthquake.[16] The site was located 2 km from the surface-projection of the blind-thrust fault. The Sylmar ground motion has a distinct pulse in both the acceleration and velocity histories, but none in the displacement history.

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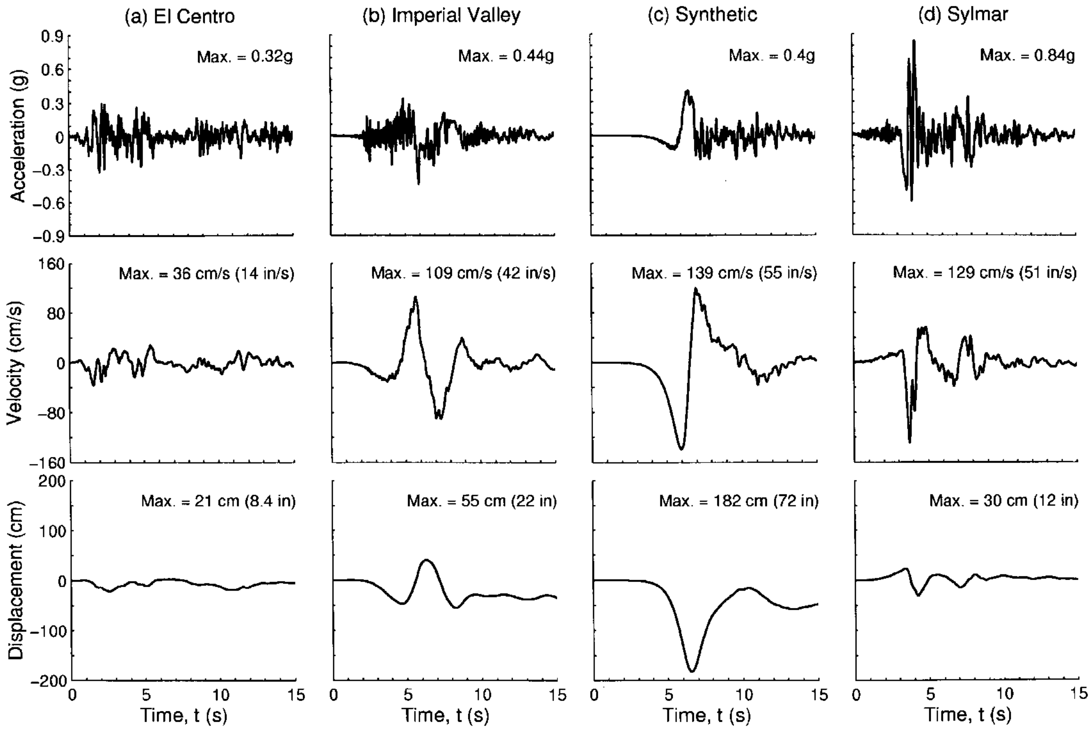

Figure 1. Acceleration, velocity and displacement histories of three recorded and one synthetic near-field ground motions

PGA, PGV *and* PGD

The peak values of ground acceleration, velocity, and displacement (PGA, PGV and PGD) for the four ground motions are compared in Figure 2. For El Centro ground motion, PGA $= 0{\cdot}32g$, PGV $= 36$ cm/s (14 in/s), and PGD $= 21$ cm (8·4 in). The PGA for the Imperial Valley ground motion is 38% higher than the El Centro value. However, PGV is 3 times and PGD 2·6 times the El Centro value. The PGA for the Synthetic ground motion is 25% higher than the El Centro value. However, PGV is nearly 4 times and PGD nearly 9 times the El Centro values. The PGA for the Sylmar ground motion is 1·9 to 2·6 times the PGA for the previous three ground motions. The PGV is greater than that for the Imperial Valley and only slightly less than that for the Synthetic ground motion. The PGD for the Sylmar ground motion is small—only 1·4 times the El Centro value and significantly smaller than that for the Imperial Valley and Synthetic ground motions.

ELASTIC RESPONSE SPECTRA

The tripartite plots of the 5% damped elastic response spectra for the four ground motions are shown in Figure 3. In these plots, the natural period T is along the horizontal axis, pseudo

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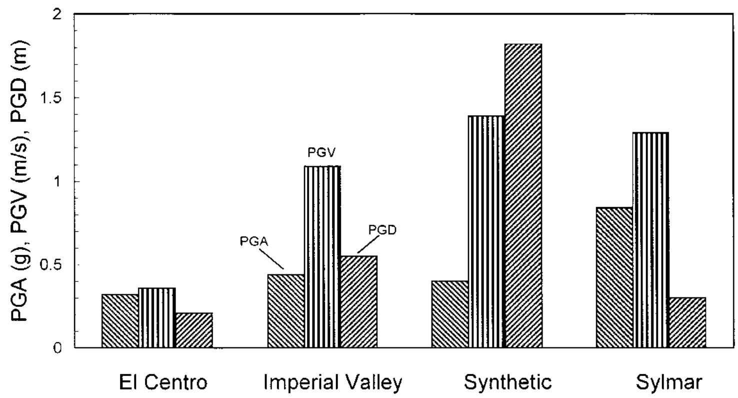

Figure 2. Peak values of ground acceleration, velocity and displacement (PGA, PGV and PGD) for three recorded and one synthetic near-field ground motions

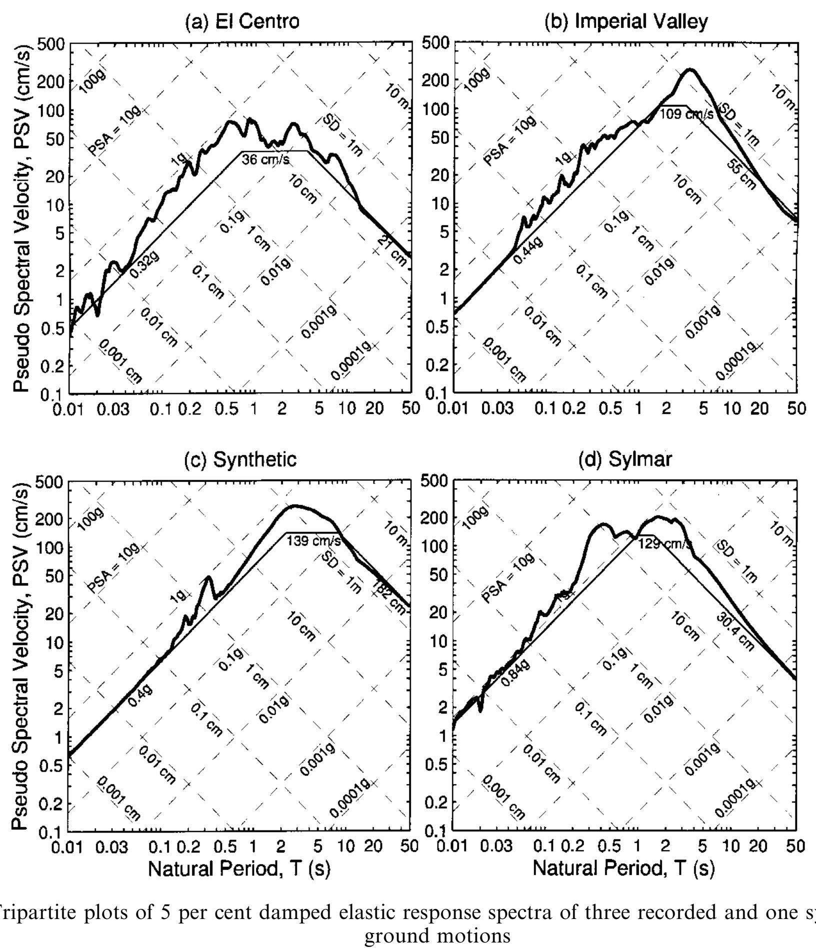

Figure 3. Tripartite plots of 5 per cent damped elastic response spectra of three recorded and one synthetic near-field ground motions

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spectral velocity PSV along the vertical axis, pseudo spectral acceleration PSA along the $-45°$ axis, and the spectral deformation SD along the $+45°$ axis. These quantities are related to each other as follows:[14]

$$\mathrm{PSA} \times \left(\frac{T}{2\pi}\right)^2 = \mathrm{PSV} \times \left(\frac{T}{2\pi}\right) = \mathrm{SD} \tag{1}$$

The PGA, PGV and PGD values are indicated by thin solid lines in Figure 3. Note that the spectral amplitudes at short periods are sensitive to the value of PGA, those at long periods are sensitive to the value of PGD, and those in the intermediate range of period are sensitive to the value of PGV. This is not surprising, because the frequencies in the ground motion that control the value of PGA also control the response of stiff (short-period) systems, frequencies that control the value of PGD also control the response of flexible (long-period) systems, and frequencies that control the value of PGV control the response of systems with intermediate stiffness.

SMOOTH ELASTIC RESPONSE SPECTRA

The plots of smoothed Newmark–Hall[17] type elastic response spectra for the first three ground motions are shown in Figure 4(a). The smoothing operation consisted of minimizing the sum of the square error (difference) between the jagged spectrum (Figure 3) and the smooth spectrum (Figure 4). In these plots, the middle region with constant pseudo spectral velocity is known as the velocity-sensitive region, the region to the left of it is known as the acceleration-sensitive region, and the region to the right of it is known as the displacement-sensitive region.[14] The spectral amplitudes in various regions depend on the values of PGA, PGV and PGD, while the widths of the various regions depend on the ratios between PGA, PGV and PGD—higher PGV/PGA ratio

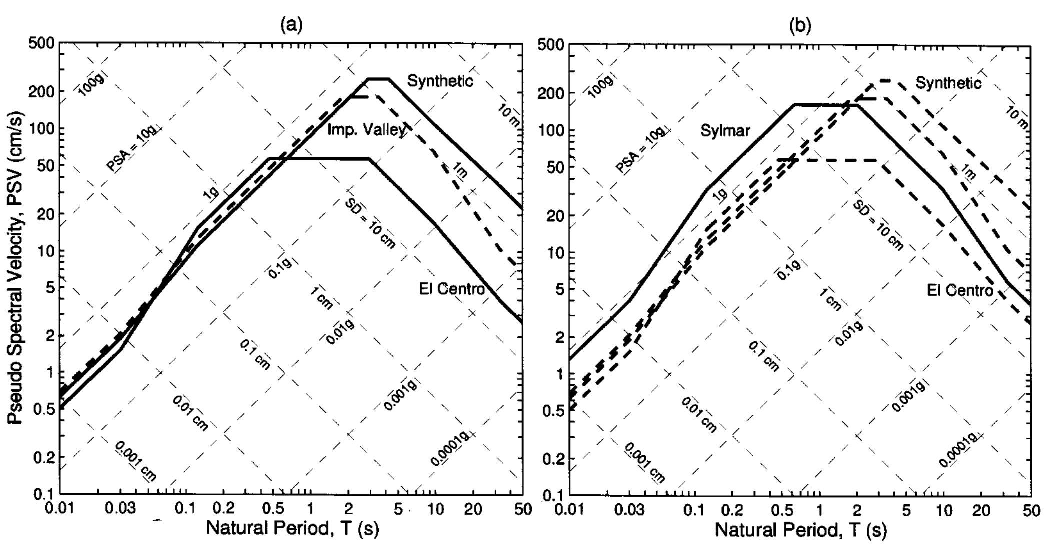

Figure 4. Tripartite plots of 5 per cent damped smooth elastic response spectra of three recorded and one synthetic near-field ground motions

Table I. PGV/PGA and PGD/PGV values for four near-field ground motions

Ground motions	PGV/PGA	PGD/PGV
1940 El Centro	0·12 s	0·58 s
1979 Imperial Valley	0·25 s	0·50 s
Synthetic[9]	0·35 s	1·31 s
1994 Sylmar	0·16 s	0·23 s

Table II. Width of acceleration-sensitive region for different ground motions

Ground motions	Width of acceleration-sensitive region
1940 El Centro	0·5 s
1979 Imperial Valley	1·8 s
Synthetic[9]	2·9 s
1994 Sylmar	0·6 s
1994 UBC (Rock Site)	0·4 s
1994 UBC (Soft Soil Site)	0·9 s
1997 UBC (Zone 4, Soil Type B, >15 km from any Seismic Source)	0·4 s
1997 UBC (Zone 4, Soil Type E, < 2 km from Seismic Source A)	1·4 s

leads to wider acceleration-sensitive region, and lower PGD/PGV ratio leads to wider displacement-sensitive region. The PGV/PGA and PGD/PGV ratios for the four ground motions are compared in Table I.

Because the PGA values for the first three ground motions are not significantly different from one another, the peak pseudo spectral accelerations for these three ground motions are also not very different [Figure 4(a)]. However, there is one significant difference—whereas, for the El Centro ground motion the acceleration-sensitive region extends up to 0·5 s, this region for the Imperial Valley and the Synthetic ground motions extends up to 1·8 and 2·9 s, respectively. The rather wide acceleration-sensitive region for the Imperial Valley and the Synthetic ground motions is due to high PGV/PGA ratio for these two ground motions—0·25 and 0·35 s, respectively, compared with 0·12 s for El Centro ground motion.

The smooth tripartite spectrum for the Sylmar ground motion is shown by solid lines in Figure 4(b). The remaining three spectra are shown by dashed lines in this figure. In the acceleration-sensitive region, the Sylmar spectrum is significantly higher than the other three spectra. In the velocity-sensitive region, the Sylmar spectrum is as high as the Imperial Valley spectrum, but in the displacement-sensitive region, the Sylmar spectrum is only higher than the El Centro spectrum. Because, PGV/PGA $= 0{\cdot}16$ s for the Sylmar record is not very high, the acceleration-sensitive region for this spectrum is only slightly wider than that for the El Centro spectrum [Figure 4(b)].

In Table II, the widths of the acceleration-sensitive regions for the four ground motion spectra are compared with those for the 1994 Uniform Building Code (UBC)[18] and 1997 UBC[19] spectra. The acceleration-sensitive regions for the Imperial Valley and the Synthetic ground motions are two and three times as wide as the widest acceleration-sensitive region recommended by the 1994 UBC. The 1997 UBC, unlike 1994 UBC, does have a provision to widen the acceleration-sensitive

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region for near-field sites, but, even the widest acceleration-sensitive region recommended by 1997 UBC is only 75 per cent as wide as that for the Imperial Valley and only 50 per cent as wide as that for the Synthetic ground motion spectra.

EFFECTS OF WIDE ACCELERATION-SENSITIVE REGION

A wide acceleration-sensitive region has following effects on the response of structures:

1. Reduced apparent flexibility: Structures behave in a stiff or flexible manner depending on whether they are in the acceleration-sensitive region of the ground motion spectrum or outside of it. Wider the acceleration-sensitive region, greater the number of structures which behave in a stiff manner. For example, a 17-storey high-rise and a 3-storey base-isolated building, both with a natural period of 2·5 s, would be considered flexible for the El Centro and Sylmar ground motions but rather stiff for the Synthetic ground motion.

2. Increased base shear and inter-storey drifts: A wide acceleration-sensitive region causes more and more modes of vibration of a high-rise building to fall within that region of the spectrum. This, in turn, causes increased elastic base shear and inter-storey drifts in high-rise buildings.

3. Reduced contribution of higher modes: A wide acceleration-sensitive region causes the fundamental mode of vibration of even a fairly tall building to remain within that region of the spectrum. Therefore, the contribution of the first mode to the base shear increases in comparison with that of the higher modes.

4. Reduced effectiveness of supplemental damping: The supplemental damping is more effective for flexible systems than for rigid systems. Because a wide acceleration-sensitive region causes many, otherwise flexible, systems to behave in a stiff manner, it reduces the benefit of supplemental damping for these systems.

5. Increased ductility demand: The ductility demand μ for a given value of the force reduction factor R_d is highest for stiff systems which fall within the acceleration-sensitive region of the spectrum.[14,20] Many systems that are in the velocity-sensitive region for the El Centro and Sylmar ground motions would be in the acceleration-sensitive region for the Imperial Valley and the Synthetic ground motions. Ductility demand for these systems would increase significantly.

The above effects are discussed in greater detail in the rest of this paper.

ACCELERATION-DEFORMATION RESPONSE SPECTRA

The acceleration-deformation response spectrum is a plot of the pseudo spectral acceleration PSA against the spectral deformation SD. Such plots are commonly used in non-linear static (push-over) analyses. The acceleration-deformation spectra for the El Centro, the Imperial Valley, and the Synthetic ground motions are shown in Figure 5(a) for 20 per cent damping. The natural period T in a plot of this type is indicated by radial lines passing through the origin. A building undergoing non-linear response with an effective period of $T = 2{\cdot}5$ s and an effective viscous damping of 20 per cent would experience a 15 cm (6 in) deformation for El Centro, 44 cm (17 in)

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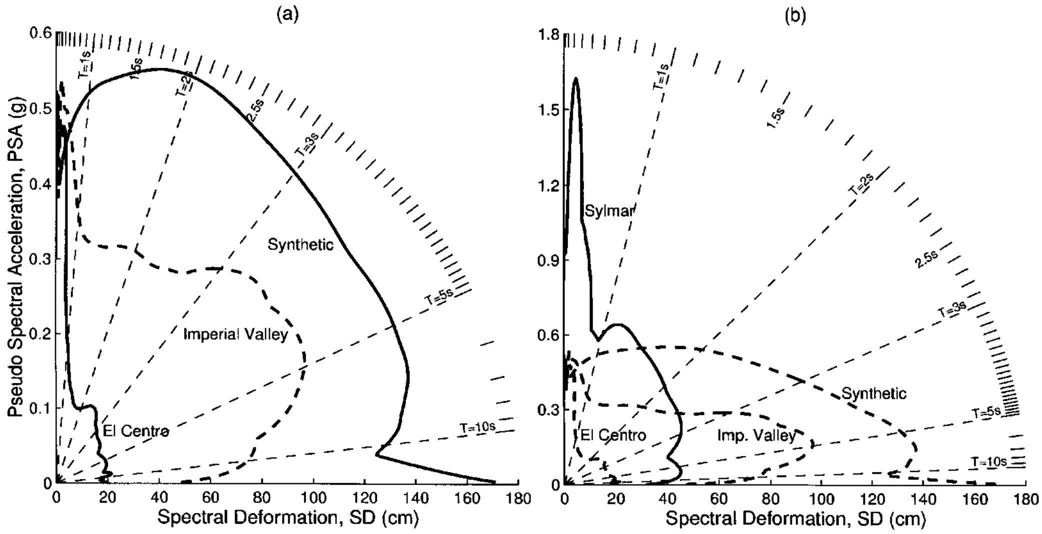

Figure 5. Acceleration-deformation plots of 20 per cent damped elastic response spectra of three recorded and one synthetic near-field ground motions

deformation for Imperial Valley, and 75 cm (30 in) deformation for Synthetic ground motion. For a high-rise building, this deformation is distributed throughout the height of the building, whereas for a base-isolated building, this deformation takes place across the isolators. The corresponding values of spectral acceleration (or the base shear coefficient) are 0·1g for El Centro, 0·29g for Imperial Valley and 0·48g for Synthetic ground motion. The deformation as well as the base shear for the Synthetic ground motion is remarkably higher than those for the El Centro ground motion.

From an acceleration-deformation spectrum it is rather easy to visualize the effect of period change on the base shear coefficient and the deformation demand. For the El Centro record, a period increase from 0·1 to 2 s causes a significant reduction in spectral acceleration (or base shear) but only a small increase in the spectral deformation [Figure 5(a)]. For the Synthetic ground motion, the same increase in period (0·1 to 2 s) does not produce a reduction in the base shear but increases the deformation demand dramatically. Therefore, base isolation (which relies on reducing base shear without significantly increasing bearing deformations) would be much less effective for the Synthetic ground motion than it would be for the El Centro ground motion.

The acceleration-deformation spectrum for the Sylmar ground motion is shown by solid lines in Figure 5(b). The spectra for other three ground motions are shown by dashed lines in this figure. The similarity between the Sylmar and the El Centro spectra is noteworthy. When the system period is increased from 0·1 to 2 s, the Sylmar spectrum, similar to the El Centro spectrum, shows a dramatic reduction in the base shear without a significant increase in the deformation demand. Base isolation is, therefore, highly effective for the Sylmar ground motion.

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DRIFT SPECTRA

The drift spectrum was introduced by Iwan[10] to illustrate the effects of near-field ground motions on high-rise buildings. It is a plot of the maximum shear strain at the base of a uniform shear beam versus the natural period of the shear beam, for a given ground motion and a specified value of the damping ratio. The strain in the shear beam is an indirect measure of the storey-drift ratio in a high-rise building. For the purpose of this study, it is considered more instructive to replace the uniform shear beam with a uniform shear building. For an assumed relationship between the number of storeys and the fundamental natural period, a plot can be generated between the number of storeys and the maximum first-storey drift. It should be noted that for a uniform shear building, the maximum storey drift depends only on the assumed relationship between the number of storeys and the building period, and on the value of the damping ratio. It does not depend on the actual storey height.

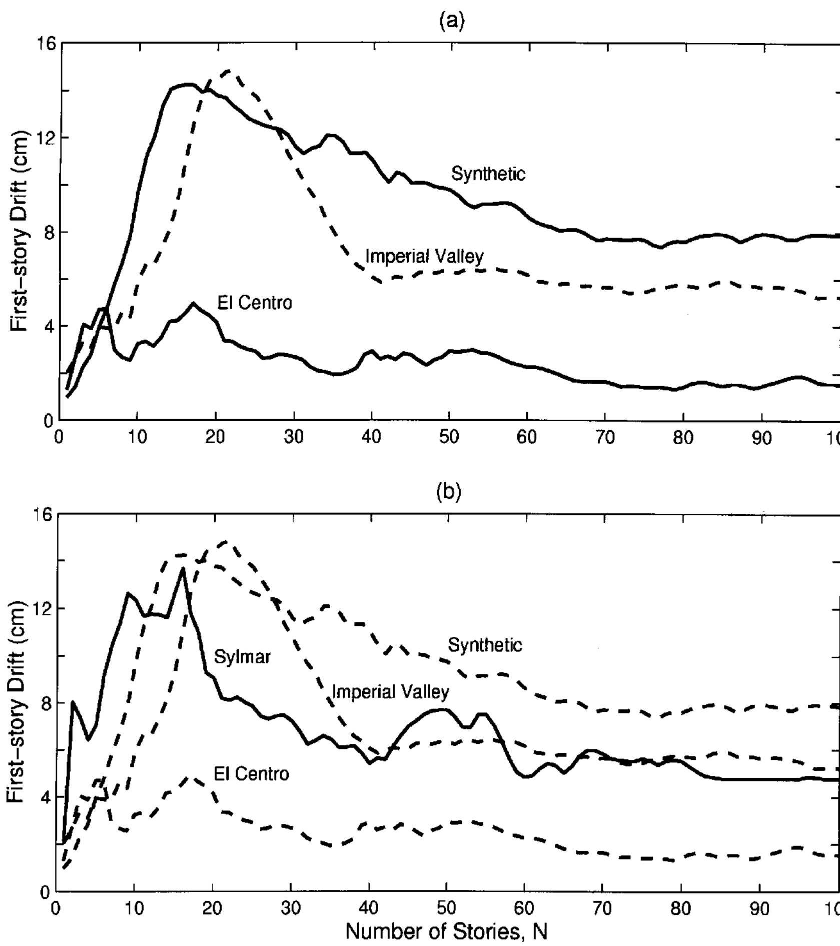

Figure 6. Drift spectra for three recorded and one synthetic near-field ground motions (Fundamental building period $T_1 = 0{\cdot}15N$, damping ratio = 2 per cent)

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Shown in Figure 6(a) are the plots of 2 per cent damped drift spectra for the El Centro, Imperial Valley, and Synthetic ground motions. The relationship between the fundamental building period T_1 and the number of storeys N is assumed to be $T_1 = 0{\cdot}15N$. Note that in Figure 6(a), the first-storey drift first increases with increase in N and then reduces. This trend is observed for all three ground motions. For the El Centro ground motion, the increase in drift continues for up to a 5-storey building. As the building height increases further, the fundamental mode and then the higher modes of vibration move out of the acceleration-sensitive region into the velocity- and displacement-sensitive regions, causing the base shear and, hence, the first-storey drift to reduce. For the Imperial Valley and the Synthetic ground motions, the acceleration-sensitive region is so wide that even for a fairly tall building the fundamental mode of vibration remains within the acceleration-sensitive region of the spectrum. As a result, the increase in the first-storey drift with increase in the number of storeys continues much longer and the drift demand for high-rise buildings becomes substantially greater than that for the El Centro ground motion.

The drift spectrum for the Sylmar ground motion is shown by solid lines in Figure 6(b). The drift spectra for the other three ground motions are shown by dashed lines in this figure. Note that the Sylmar ground motion causes large drifts in only low- to medium-rise buildings which fall within its acceleration- or velocity-sensitive regions. For high-rise buildings, the Sylmar ground motion is not as severe as the Imperial Valley or the Synthetic ground motions due to relatively small spectral values in the displacement-sensitive region of the Sylmar spectrum [Figure 4(b)].

ROOF DISPLACEMENT SPECTRA

Shown in Figure 7(a) are the plots of the roof displacement for uniform shear buildings of different number of storeys, subjected to the first three ground motions. The displacement of the roof relative to ground is dominated by the first mode of vibration of the building and is greatest when the first mode falls within the displacement-sensitive region of the spectrum. Because the Synthetic ground motion spectrum is largest in the displacement-sensitive region [Figure 4(a)], the roof displacement for this ground motion is significantly higher than that for the El Centro and the Imperial Valley ground motions.

The roof displacement spectrum for the Sylmar ground motion is shown by solid lines in Figure 7(b). The roof displacement spectra for the other three ground motions are shown by dashed lines in this figure. Note that for high-rise buildings the roof displacements due to the Sylmar ground motion are significantly smaller than those due to the other two pulse-like ground motions (Imperial Valley and Synthetic), and only slightly larger than those due to the El Centro ground motion. This again is due to smaller spectral values in the displacement-sensitive region of the Sylmar spectrum.

HIGHER MODE CONTRIBUTION

It has been argued that the pulses in the near-field ground motion travel through the height of buildings as waves, and such response is dominated by the higher modes of vibration of the building.[10] This is investigated here. In Figure 8, the percentage contribution of higher modes to the first-storey drift for three pulse-like ground motions is compared with that for the El Centro motion. For reasons explained earlier, the contribution of the higher modes to the first-storey

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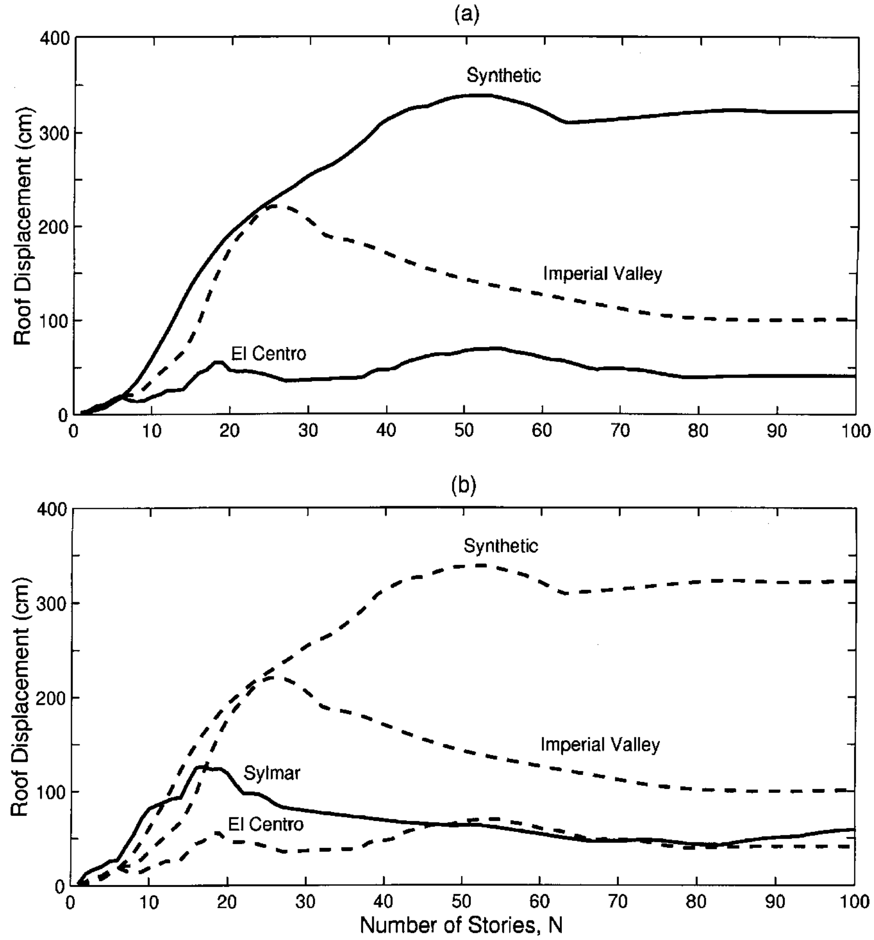

Figure 7. Roof displacement spectra of three recorded and one synthetic near-field ground motions (Fundamental building period $T_1 = 0{\cdot}15N$, damping ratio = 2 per cent)

drift increases with increase in the number of storeys in the building. For the Sylmar ground motion (with narrower acceleration-sensitive region), the higher mode contribution becomes truly significant as the number of storeys in the building exceeds 20, whereas for the Imperial Valley and the Synthetic ground motions (with wider acceleration-sensitive regions), the higher mode contribution becomes significant only for buildings taller than 42 and 46 storeys, respectively. For the El Centro motion, the higher mode contribution becomes significant for buildings taller than 19 storeys.

For Sylmar motion the higher mode contribution is remarkably high compared with the other three ground motions. For a 30-storey building (period, $T_1 = 4{\cdot}5$ s), the higher mode contribution to first-storey drift is negligible for the Imperial Valley and Synthetic ground motions, 34 per cent for the El Centro motion, and 52 per cent for the Sylmar motion. This needs further

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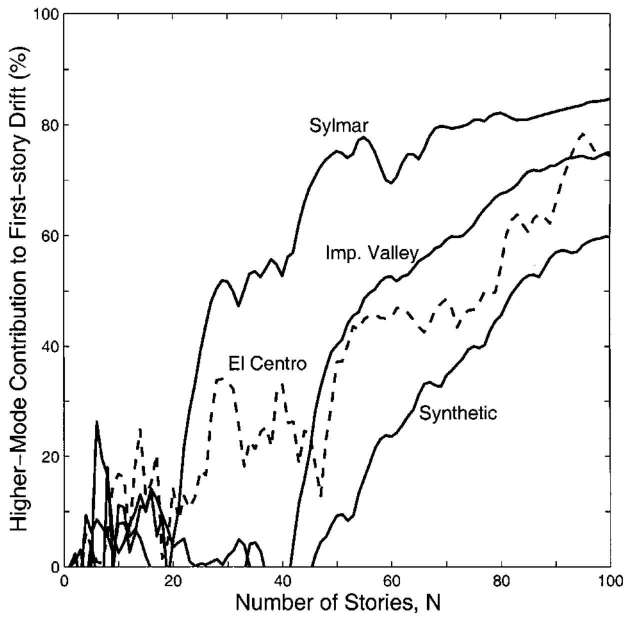

Figure 8. Higher modes contribution to first-storey drift for three pulse-like ground motions and 1940 El Centro ground motion ($T_1 = 0{\cdot}15N$, damping ratio = 2 per cent)

clarification. The Sylmar motion has high PGA and PGV values, but low PGD value (Figure 1). Of the four ground motions, the Sylmar motion has the lowest PGD/PGV value (Table I). Therefore, the displacement-sensitive region for the Sylmar motion begins much sooner (at period = 2·1 s), as compared with 3·5 s for Imperial Valley, 4·2 s for Synthetic, and 3 s for El Centro motion (Figure 4). As a result, the fundamental period of the 30-storey building is well within the displacement-sensitive region of the Sylmar spectrum, while it is barely in the displacement-sensitive region of the Imperial Valley and Synthetic ground motion spectra. The fundamental mode therefore contributes much less to the first-storey drift for the Sylmar motion than for the other two pulse-like ground motions.

EFFECTIVENESS OF SUPPLEMENTAL DAMPING

The supplemental damping is provided in buildings to reduce the displacements and inter-storey drifts. The supplemental damping is not highly effective for very stiff or very flexible buildings. Buildings in the intermediate range of stiffness (which fall in the longer-period part of the acceleration-sensitive region and throughout the velocity-sensitive region) benefit most from supplemental damping.[14] The plots in Figure 9 show the percentage reduction in the first-storey drift in buildings of various number of storeys, due to an increase in the viscous damping from 2 per cent to 20 per cent. Note that for low- to medium-rise buildings the supplemental viscous damping is not very beneficial for the Imperial Valley and the Synthetic ground motions as it is for the El Centro or Sylmar ground motions. As mentioned earlier, for the Imperial Valley and

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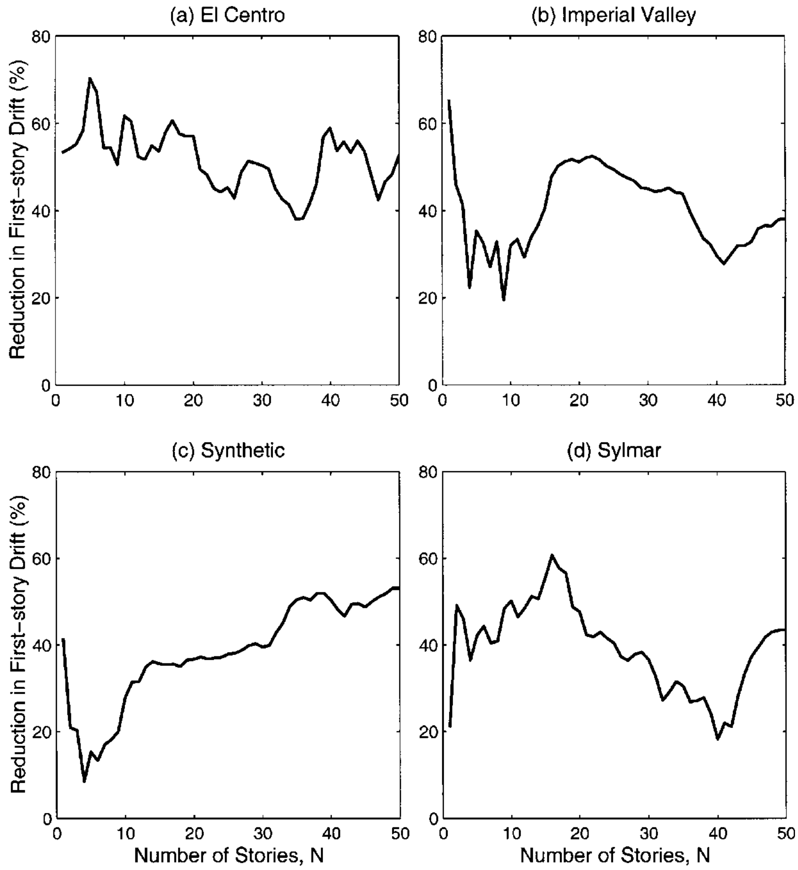

Figure 9. Reduction in first-storey drift due to an increase in viscous damping from 2 to 20 per cent ($T_1 = 0.15N$)

Synthetic ground motions the velocity-sensitive region is pushed to longer periods, hence high-rise buildings benefit more from supplemental damping than low- to medium-rise buildings. The average reduction in the first-storey drift for buildings up to 20-storey high is 57 per cent and 45 per cent, respectively, for El Centro and Sylmar ground motions, and 35 and 25 per cent, respectively, for Imperial Valley and Synthetic ground motions.

DUCTILITY DEMAND

Buildings are rarely designed to remain fully elastic during strong ground shaking. They are allowed to yield at a force which is usually a fraction of the elastic force. In order to prevent collapse, a building should possess a certain amount of ductility. For a given ground motion, a relationship can be established between the force-reduction factor R_d (= elastic force/yield force) and the ductility ratio μ (= inelastic deformation/yield deformation). In Figure 10(a), the

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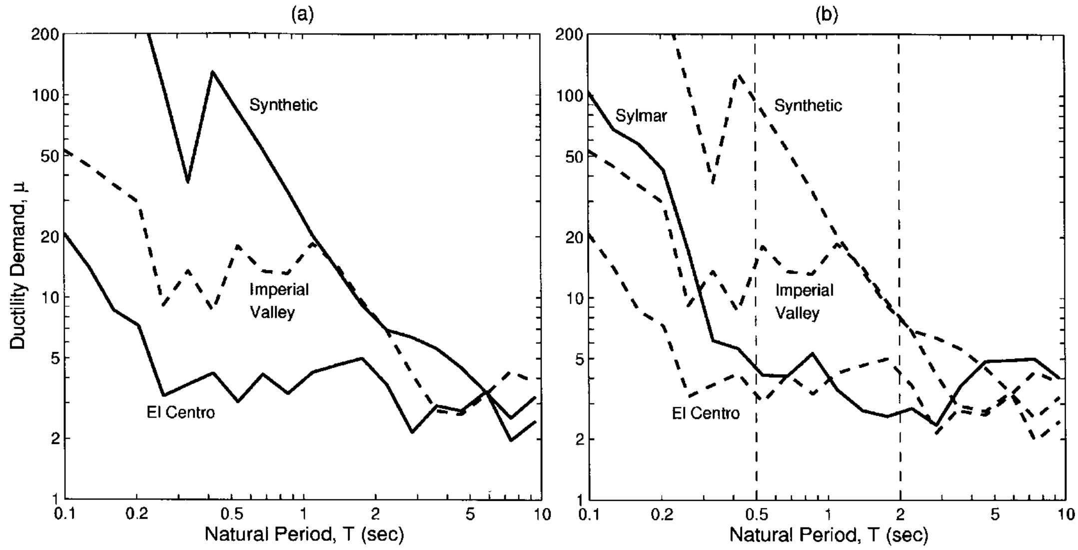

Figure 10. Ductility demand for SDOF elastoplastic systems due to different ground motions ($R_d = 4$, damping ratio $= 2$ per cent)

ductility ratio μ for elastoplastic, single-degree-of-freedom (SDOF) system subjected to the first three ground motions is plotted against the elastic natural period of the SDOF system, for force reduction factor $R_d = 4$. The ductility demand for the Imperial Valley and the Synthetic ground motions is clearly much higher than that for the El Centro ground motion, due to significantly higher deformation demand imposed by the former two ground motions [Figure 5(a)]. The ductility demand for the Sylmar ground motion is shown by solid lines in Figure 10(b), while that for the other three ground motions is shown by dashed lines in this figure. Note that in the period range of 0·5–2 s, the ductility demand for the Sylmar ground motion is nearly same as that for the El Centro ground motion and significantly smaller than that for the Imperial Valley and Synthetic ground motions. The period range of 0·5–2 s falls mostly in the acceleration-sensitive region of the Imperial Valley and Synthetic ground motion spectra, but it falls in the velocity-sensitive region of the El Centro and Sylmar ground motion spectra. Because the ductility demand is highest in the acceleration-sensitive region,[14,20] the Imperial Valley and Synthetic ground motions impose much higher ductility demand than the El Centro and Sylmar ground motions, for the same value of the force-reduction factor R_d.

COMPARISON WITH 1997 UBC SPECTRUM

The 5 per cent damped spectrum for Seismic Zone 4 in the 1997 UBC is defined in terms of seismic coefficients C_a and C_v and a Near-Source Factor N_v.[19] A plot of this spectrum is shown in Figure 11. The peak ground acceleration implied in the UBC 1997 spectrum is

$$\mathrm{PGA}(g's) = C_a \tag{2}$$

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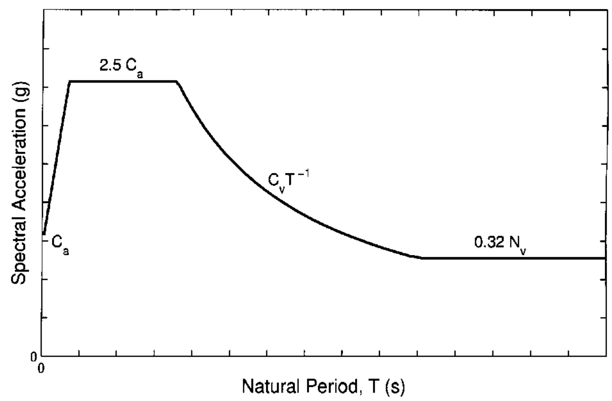

Figure 11. 1997 Uniform Building Code (UBC) spectrum for 5 per cent damping

and the maximum value of the pseudo spectral velocity PSV, in the velocity-sensitive region, is

$$\mathrm{PSV} = g \times \frac{C_v}{T} \times \frac{T}{2\pi} = \frac{gC_v}{2\pi} \tag{3}$$

Assuming an amplification factor of 1.65 between peak ground velocity PGV and pseudo spectral velocity PSV,[14,17] the value of PGV can be estimated as

$$\mathrm{PGV} \approx \frac{gC_v}{2\pi \times 1{\cdot}65} \approx 95C_v(\mathrm{cm/s}) \tag{4}$$

In the displacement-sensitive region, the UBC 1997 spectrum is not reasonable, because it does not allow the spectral acceleration to drop below the 'floor' value of $0{\cdot}32N_v$, where N_v varies between 1 and 2 depending on the distance from and type of the Seismic Source. This lower limit on spectral acceleration causes the spectral deformation to increase without bound for very flexible systems. It amounts to assuming an infinite value of the peak ground displacement.

For a soil (Type D) site in Seismic Zone 4, at a distance 2 km from a Seismic Source Type A, the values of C_a and C_v obtained from 1997 UBC[19] are 0.66 and 1.28, respectively. The assumed site characteristics are similar to those for the site of the Imperial Valley ground motion. The implied values of PGA and PGV in the 1997 UBC spectrum for this site, obtained from equations (2) and (4), are PGA $= 0{\cdot}66g$ and PGV $= 122$ cm/s. For the UBC ground motion, the PGA and PGV are both higher than the Imperial Valley ground motion values, therefore, the UBC spectrum in Figure 12(a) nearly completely envelopes the Imperial Valley spectrum.

For a soil (Type D) site in Zone 4, at 2 km from Seismic Source Type B, the C_a and C_v values from 1997 UBC are 0·57 and 1·02, respectively, hence, the implied value of PGA and PGV are $0{\cdot}57g$ and 97 cm/s, respectively. This site is similar to the site of the Synthetic and Sylmar ground motions. Plots in Figure 12(b) show that compared with the Synthetic ground motion spectrum, the UBC spectrum is quite conservative in the acceleration-sensitive region and unconservative in the velocity-sensitive region. Plots in Figure 12(c) show that the UBC spectrum matches the Sylmar spectrum reasonably well in the acceleration- and velocity-sensitive regions.

In the displacement-sensitive region, the UBC spectrum is clearly unrealistic.

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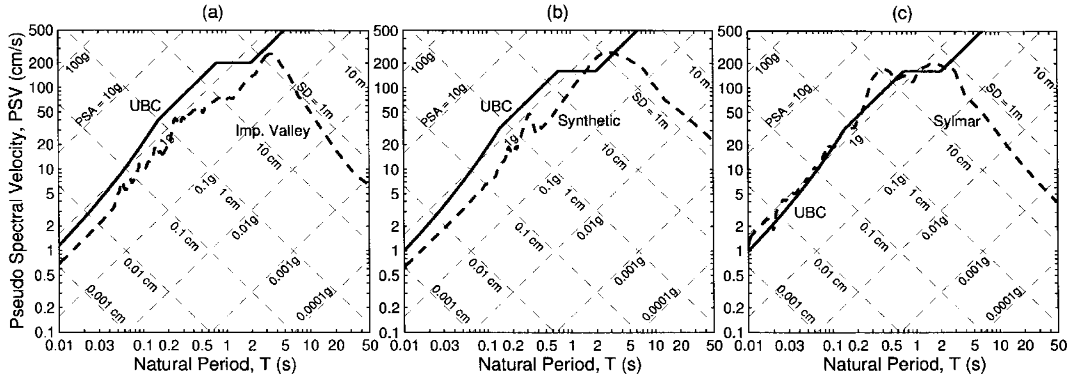

Figure 12. Comparison between 5 per cent damped 1997 UBC spectra, and two recorded and one synthetic near-field ground motion spectra. The UBC spectrum in part (a) is for Zone 4, Soil Type D, at distance of 2 km from Seismic Source Type A. The UBC spectrum is parts (b) and (c) is for Zone 4, Soil Type D, at distance of 2 km from Seismic Source Type B

CONCLUSIONS

The response characteristics of two recorded and one synthetic near-field pulse-like ground motions were compared with those of the 1940 El Centro ground motion which does not contain any directivity pulses. Following conclusions are based on the dynamic response of elastic multi-degree-of-freedom systems and inelastic single-degree-of-freedom systems:

1. Pulse-like ground motions with high PGV/PGA ratio have wide acceleration-sensitive region in their elastic response spectrum. This has following effects on the response of structures:

   - Reduced apparent flexibility of high-rise and base-isolated buildings;
   - Increased base shear and inter-storey drifts in high-rise buildings;
   - Reduced effectiveness of supplemental damping; and
   - Increased ductility demand.

   Pulse-like ground motions with low PGV/PGA ratio have the opposite effects on the response of structures.
2. Pulse-like ground motions with high PGV/PGA ratio show smaller contribution from higher-modes, while pulse-like ground motions with relatively low PGV/PGA ratio show larger contribution from higher modes. Higher mode contribution for pulse-like ground motions is not always greater than that for ground motions without directivity pulses.
3. The shape of the elastic response spectrum alone can explain some effects of near-field pulse-like ground motions on the elastic response of high-rise buildings. These include the contribution of higher modes, effectiveness of supplemental damping, and increased base-shear and first-storey drift.
4. Peak values of ground acceleration, velocity and displacement (PGA, PGV and PGD) are the key parameters that control the response characteristics of near-field pulse-like ground

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motions. The presence of pulses in the acceleration, velocity or displacement histories does not appear to be as significant as the actual values of PGA, PGV and PGD.

5. Pulses in ground motion histories do not always result in large contribution from higher-modes in high-rise buildings. Therefore, the wave-propagation analysis is not necessarily required for every pulse-like ground motion. Whereas, it may be considered suitable for ground motions with low PGV/PGA ratio (e.g. Sylmar motion), it does not appear to be needed for pulse-like ground motions with relatively high PGV/PGA ratio (e.g. Imperial Valley and Synthetic ground motions).
6. For near-field sites, the 1997 UBC spectrum appears to be less conservative in the velocity-sensitive region than in the acceleration-sensitive region. The UBC spectrum is overly conservative in the displacement-sensitive region, hence, unsuitable for the design of very flexible systems.
7. It is felt that the response spectrum in the building codes should be defined in terms of PGA, PGV and PGD values rather than some factors dependent on these values. This will allow easy comparison between the code specified ground motions and other recorded and synthetic ground motions.

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APPENDIX I

Notation

C_a	seismic coefficient in acceleration-sensitive region of UBC 1997 spectrum
C_v	seismic coefficient in velocity-sensitive region of UBC 1997 spectrum
N_v	near-source factor in UBC 1997
PGA	peak ground acceleration
PGD	peak ground displacement
PGV	peak ground velocity
PSA	pseudo spectral acceleration
PSV	pseudo spectral velocity
R_{d}	force-reduction factor due to ductility (elastic force/yield force)
SD	spectral deformation
SDOF	single-degree-of-freedom system
T	undamped natural period of single-degree-of-freedom system
T_1	fundamental period of a multi-storey building
μ	ductility ratio (inelastic deformation/yield deformation)

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